VOLT-HERTZ CONTROL OF THE SYNCHRONOUS MOTOR WITH RAMP EXCITING VOLTAGE

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Abstract – **The constant Volt/Hertz method is an empirical feed-forward scalar control procedure used in open-loop in order to maintain the rated flux level of the AC machine ensuring the optimal use of the drive capabilities. The main drawback of the constant Volt/Hertz procedure consists on the effects of the voltage drops at low frequencies. This can be eliminated by adopting different techniques, for the voltage drop compensation. The paper deals with the Voltage-Hertz control of a salient-pole synchronous motor with variable, ramp exciting voltage, with current-feedback-based voltage-drop compensation.**

Keywords: *synchronous motor, Volt-Hertz control, variable exciting field, voltage-drop compensation.*

1. INTRODUCTION

In various industrial applications, where is no need for high dynamical performance (like pumps, ventilators, etc.), for variable speed AC drives scalar control procedures are used. Most of the electrical drives, present on the market, include besides the vector control, also scalar control based strategies.

Generally, the scalar control is used in reduced speed-range applications ($\omega_{min}/\omega_{max} \approx 1{:}10$). Historically the first loss-less control method for the AC machines was the so-called constant Volt/Hertz control.

In industrial applications, the Volt/Hertz control is frequently used, due to its simplicity. The stator construction of the induction and the synchronous machines are the same, consequently this control method can be applied without any changes for both motor types. Because the synchronous motor operates at synchronous speed, there are no slip-related problems to be solved in comparison with other motor types. The mechanical characteristics (speed-torque) are constant, only the load angle will be variable with respect to the load torque modification, which has no importance in this scalar control procedure.

In case of the Voltage-Hertz control, the constant stator-flux operation is obtained empirically, (no flux identification is required) by an open-loop feed-forward scalar control procedure, without mechanical sensors. The only reference variable is the supply frequency, while the stator-voltage is computed based on the simplified steady-state equivalent circuit of the stator. For a certain value of the Ω_s fundamental frequency of the stator-voltage and m_L load torque (which determines the magnitude of the I_s stator current), if the exciting field is constant, the resulting stator flux is determined only by U_s stator voltage. In order to obtain rated flux value, the steady-state stator-voltage equation has to be fulfilled:

$$\underline{U}_s = R_s \underline{I}_s + j\Omega_s \underline{\Psi}_s = \left(R_s + j\Omega_s L_{\sigma s}\right)\underline{I}_s + j\Omega_s \underline{\Psi}_m \,. \quad (1)$$

For the U_s prescribed value, the modification of the I_s leads to the variation of the EMF, and consequently to the variation of the resultant stator flux. In order to restore the flux, the stator voltage has to be adjusted. The variation of the Ω_s also leads to the variation of the EMF, and of the flux, too. The flux can be restored only by adjusting the stator voltage in such a manner, that its value will depend strictly on the frequency.

From equation (1) the EMF can be expressed in vectorial form, as follows:

$$\underline{E}_s = j\Omega_s \underline{\Psi}_s \ , \quad (2)$$

or in scalar form:

$$E_s = \Omega_s \Psi_s = 2\pi f_s \Psi_s \ . \quad (3)$$

If the stator flux Ψ_s is indirectly controlled, then

$$\Psi_s = \frac{1}{2\pi}\frac{E_s}{f_s} = \frac{1}{2\pi}\frac{E_{sN}}{f_{sN}} = ct. \quad (4)$$

i.e. the mathematical form of the constant Volt/Hertz principle. If (1) is respected, it inherently contain the compensation with the voltage drop: $\Delta u = R_s I_s$.

By neglecting the stator resistance, results:

$$\Psi_s \cong \frac{1}{2\pi}\frac{U_s}{f_s} \,. \quad (5)$$

From the above expression, one can observe the origin of the procedure name, i.e. “constant Volt/Hertz control”. The role of this control method is to ensure the dependence of the stator voltage on the frequency.

Fig. 1 presents the block diagram of the salient-pole synchronous motor drive system, using the constant Volt/Hertz scalar control procedure. Considering the reference frequency f_s^{Ref}, the amplitude U_s^{Ref} and synchronous angular speed Ω_s of the stator-voltage vector is computed by means of the "V-Hz Control Block" block. It provides the input signals, which are serving as parameters for the block "3~ Sine Wave Generator". This block generates the modulation signals of the three-phase sine-wave stator-voltage. The Voltage-Source Inverter "amplifies" them and drives the synchronous motor.

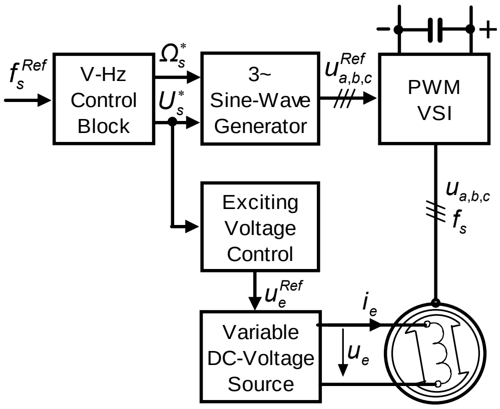

Figure 1. Block diagram of a salient-pole synchronous motor drive system, based on the Volt/Hertz scalar procedure using variable exciting field.

The basic arrangement usually is without feed-back, because the original control method was a feed-forward one, consequently it has not required any feedback for the computation of the control variables. The excitation winding is fed by a variable DC-supply. This DC-voltage is computed in the "Exciting Voltage Control" block. In this paper it will be considered independent and dependent on the computed stator voltage value, respectively. In such a case the stator-voltage reference may be computed approximately according the following expression:

$$U_s^{Ref} = U_{sN} \frac{f_s}{f_{sN}}, \tag{6}$$

where: U_{sN} is the rated stator voltage, f_s the actual stator frequency and f_{sN} its rated value.

Nevertheless, the main drawback of the constant Volt/Hertz procedure consists in the effect of the stator-voltage drop, which causes difficulties, especially at low speed operation. The voltage drop at low frequencies has the same order of magnitude as the computed voltage and it makes the method inadequate for low speed region. This problem can be eliminated by adopting different improving techniques, like: programmed voltage versus frequency characteristics [3], formula based voltage-drop compensation [2] or voltage-drop compensation using current feedback [4], [5]. Neither of the two methods takes into account the load effect.

In the third case the motor load is taken into account by means of the actual stator current. That means the computing of the stator-voltage reference is performed according to the characteristic from Fig. 2 [4], as follows:

$$U_s^{Ref} = \sqrt{2}\left(R_s I_s^{rms} + \frac{U_{sN}^{rms} - R_s I_s^{rms}}{f_{sN}} f_s^{Ref} \right). \tag{7}$$

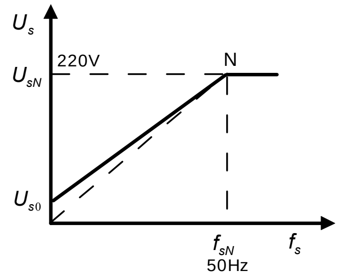

Figure 2. Voltage–frequency diagram for the current-compensated Volt/Hertz method.

The variable slope of the curves is due to the current dependent U_{s0} value and it is given by the expression:

$$\sqrt{2}\left(\frac{U_{sN}^{rms} - R_s I_s^{rms}}{f_{sN}} \right).$$

From the control diagram it can be observed that the control law is defined so, that all curves cross the motor rated working point (220 V / 50 Hz).

2. CONSTANT VOLTAGE-HERTZ CONTROL WITH VARIABLE EXCITING FIELD

In case of the synchronous motors there are some well known problems related to the starting procedure. One of the classical starting procedures requires an additional machine, which is used to start the unexcited motor. When the speed reaches the rated speed, the DC supply is connected to the exciting winding, and the motor will fall in step. It requires perfect timing, for this reason the starting procedure is difficult especially for high power motors. More problems are caused if the motor is loaded. The motor with dumper windings (i.e. usual a squirrel-cage) may be started in asynchronous mode. In this case the current in the dumper windings (short-circuited damper bars) develops the required starting torque for the motor. The induced voltage at the synchronous speed or near it will be zero. At this point the excitation is supplied with DC voltage in order to achieve the synchronous operation mode.

If the motor is fed by a Static Frequency Converter (SFC), a variable frequency starting is possible, so the Voltage-Hertz procedure can be adequate. In order to ensure a smooth starting, variable exciting field may be applied, which magnitude is also proportional to the reference frequency. The variation is linear, and it achieves the rated value at rated speed. This method is developed in order to improve the dynamic behavior of the constant Volt/Hertz procedure. Another advantage consists in the fact that changing the control law, which computes the excitation voltage, different operation parameters can be obtained, namely an indirect feed-forward control of the power factor.

3. THE MATHEMATICAL MODEL OF THE SALIENT-POLE SYNCHRONOUS MOTOR

In order to perfor m the simulation of the above control methods, the mathematical model of the synchronous motor and its control system has to be developed. The model is expressed in state-equation deduced form general equations [1]. They are written in rotor-oriented reference-frame ($d\theta - q\theta$), using the space-phasor theory [1]. In the voltage equations the state variables will be the fluxes, as follows:

$$\begin{aligned}
&\frac{d\Psi_{sd\theta}}{dt} = u_{sd\theta} - R_s \cdot i_{sd\theta} + \omega \cdot \Psi_{sq\theta};\\
&\frac{d\Psi_{sq\theta}}{dt} = u_{sq\theta} - R_s \cdot i_{sq\theta} - \omega \cdot \Psi_{sd\theta};\\
&\frac{d\Psi_{e}}{dt} = u_{e} - R_e \cdot i_{e};\\
&\frac{d\Psi_{A_d}}{dt} = -R_{A_d} \cdot i_{A_d} \qquad u_{A_d} = 0;\\
&\frac{d\Psi_{A_q}}{dt} = -R_{A_q} \cdot i_{A_q} \qquad u_{A_q} = 0.
\end{aligned} \tag{8}$$

The input variables are the voltages; ω is the rotor electrical angular speed resulting from the motion equation by the integration. The output variables - the currents can be expressed by means of algebric expressions depending on the flux-linkages:

$$\begin{aligned}
&i_{sd\theta} = \frac{1}{L''_{sd}}\Psi_{sd\theta} - \frac{1}{L''_{m(sd\theta-e)}}\Psi_e - \frac{1}{L''_{m(sd\theta-A_d)}}\Psi_{A_d}\\
&i_e = \frac{1}{L''_e}\Psi_e - \frac{1}{L''_{m(sd\theta-e)}}\Psi_{sd\theta} - \frac{1}{L''_{m(e-A_d)}}\Psi_{A_d} +\\
&i_{A_d} = \frac{1}{L''_{A_d}}\Psi_{A_d} - \frac{1}{L''_{m(sd\theta-e)}}\Psi_{sd\theta} - \frac{1}{L''_{m(e-A_d)}}\Psi_e\\
&i_{sq\theta} = \frac{1}{L''_{sq}}\left(\Psi_{sq\theta} - \frac{L_{mq}}{L_{A_q}}\Psi_{A_q}\right)\\
&i_{A_q} = \frac{1}{L''_{A_q}}\left(\Psi_{A_q} - \frac{L_{mq}}{L_{A_q}}\Psi_{sq}\right)
\end{aligned} \tag{9}$$

Where the s indices refers to the stator, the e to the excitation and A to the dumper circuit quantities. $d\theta$ and $q\theta$ indicate the rotor-oriented direct (longitudinal) and quadrature (transversal) variables, respectively. In expressions (9) L_s, L_e and L_A are the stator-, exciting- and dumper-circuit inductances, L_m the useful inductance. The sub-transient direct-axis inductances:

$$L''_{sd} = \frac{\Delta_d}{L_e L_{A_d} - L^2_{md}} \qquad L''_{Ad} = \frac{\Delta_d}{L_{sd} L_e - L^2_{md}}$$

$$L''_e = \frac{\Delta_d}{L_{sd} L_{A_d} - L^2_{md}} \tag{10}$$

$$\Delta_d = L_{sd} L_e L_{A_d} - L^2_{md}\left(L_{\sigma s} + L_{\sigma e} + L_{\sigma A_d}\right) - L^3_{md}$$

The sub-transient direct-axis mutual inductances are:

$$L''_{m(sd\theta-e)} = \frac{\Delta_d}{L_{md} L_{\sigma A_d}} \qquad L''_{m(sd\theta-A_d)} = \frac{\Delta_d}{L_{md} L_{\sigma e}}$$

$$L''_{m(e-A_d)} = \frac{\Delta_d}{L_{md} L_{\sigma s}} \tag{11}$$

The sub-transient quadrature-axis inductances are:

$$L''_{sq} = L_{sq} - \frac{L^2_{mq}}{L_{A_q}} \qquad L''_{A_q} = L_{A_q} - \frac{L^2_{mq}}{L_{sq}} \tag{12}$$

The last state-equation is obtained from the motion equation:

$$\frac{d\omega}{dt} = \frac{z_p}{J} \cdot \left[\frac{3}{s} z_p (\Psi_{sd\theta} \cdot i_{sq\theta} - \Psi_{sq\theta} \cdot i_{sd\theta}) - m_L\right], \tag{13}$$

where m_e is the electromagnetic torque, m_L the load torque, z_p the number of the pole pairs and J the moment of inertia.

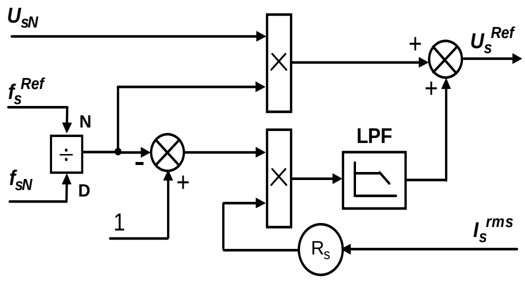

Figure 3. Simulation structure of the V-Hz control.

The structure of the “V-Hz Control Block”, based on expression (7), is shown in the figure 3. In order to eliminate electromagnetic perturbations, the compensation term is filtered using software implemented Low Pass Filter (LPF).

4. SIMULATION RESULTS

For validation of the proposed voltage-drop compensation technique, computer simulation was performed, using the MATLAB/Simulink dynamic simulation environment.

The name-plate data of the salient-pole synchronous motor are: the rated power $P_N = 800$ W, stator frequency $f_{sN} = 50$ Hz, stator voltage $U_{sN} = 220$ V, rated speed $n_N = 1500$ rpm, stator current $i_{sN} = 1.52$ A, power factor $\cos\varphi_N = 0.8$ (capacitive) and the number of pole pairs $z_p = 2$.

A speed-dependent linear load-torque profile is applied, i.e. its value increases from the motor no-load torque (at zero speed) to the rated electromagnetic torque (at the rated speed) corresponding to the steady-state operation:

$$m_L = \left[\left(m_{eN} - m_0\right)\left(\frac{|\omega|}{\omega_N}\right) + m_0 \right] sign\left(\omega\right), \quad (14)$$

where m_{eN} is the rated electromagnetic torque, m_0 the no-load torque.

The motor is controlled using the Volt/Hertz scalar control procedure, where the reference frequency has a ramp variation profile during the starting procedure. The initial conditions were the followings: the salient-pole synchronous motor with damper windings is started with the excitation winding supplied form a DC-voltage source. There were simulated two cases. In both cases the exciting voltage has also a ramp variation profile. In the first case, the exciting voltage reaches the imposed value before the stator voltage achieves his rated value. In the second case, the exciting voltage ramp is determined so, that will reach the imposed reference at the same moment than the stator voltage reaches its rated value. It means, that $U_s / U_e = ct.$

4.1. Current feedback-based compensation with ramp-voltage excitation and $U_s / U_e \neq ct.$

The initial conditions for this simulation were: the starting procedure from 0 to 50 Hz is 1.5 s, while the excitation voltage achieves the imposed value in 1 s.

Two different cases were simulated, at 0.8 capacitive – figures 4 to 6 – and unity power factor – figures 7 to 9 –in steady-state operation.

4.1.1. Results for $\cos\varphi = 1$

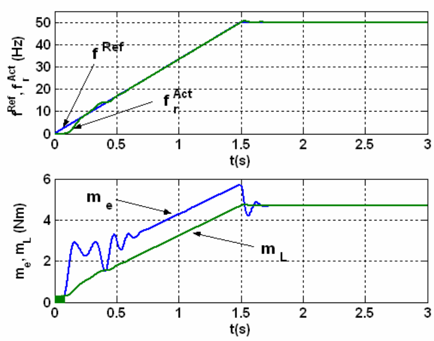

Figure 4. Stator frequency (f_s^{Ref} – reference value, f_s^{act} – actual value) and torques (m_e – electromagnetic, m_L – load) versus time.

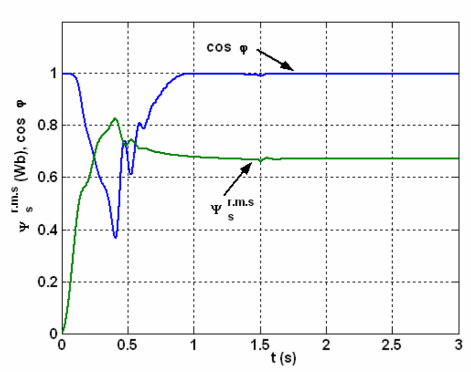

Figure 5. Power factor ($\cos\varphi$) and stator flux r.m.s. value (Ψ_s^{rms}) versus time.

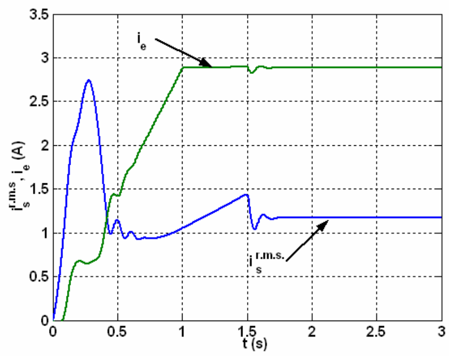

Figure 6. Stator current r.m.s. value (i_s^{rms}) and excitation current (i_e) versus time

From the obtained results can be observed that also in this case, when variable excitation is applied, the constant Volt/Hertz control performs well.

The indirect flux control is maintained, however, an overshot occurs during the starting procedure, which is caused by the voltage-drop compensation procedure. Because of this, at certain moments overcompensation may appear, and for this period the constant Volt/Hertz ratio is lost.

4.1.2. Results for $\cos\varphi = 0.8$

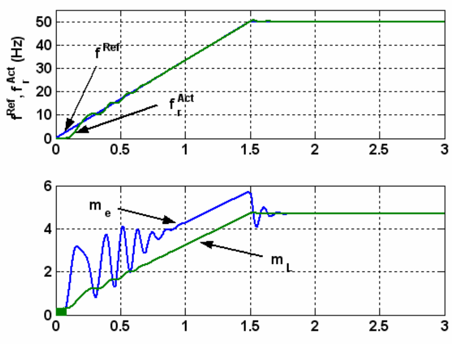

Figure 7. Stator frequency (f_s^{Ref} – reference value, f_s^{act} – actual value) and torque (m_e – electromagnetic and m_L – load) versus time.

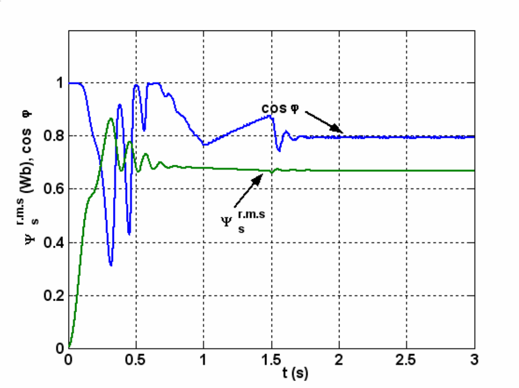

Figure 8. Power factor ($\cos\varphi$) and stator flux r.m.s. value (Ψ_s^{rms}) versus time.

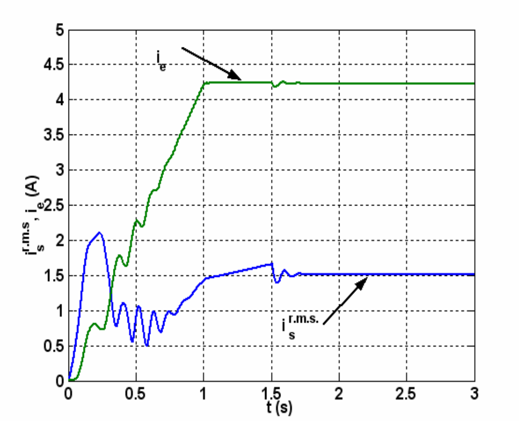

Figure 9. Stator current r.m.s. value (i_s^{rms}) and excitation current (i_e) versus time

The instability during the starting procedure is amplified in case of capacitive power factor operation, when the excitation voltage is higher. Because the exciting voltage variation ramp is faster than the frequency variation ramp, the motor is over-excited. However, in steady state operation mode the stability is maintained. In spite of this problem, in some applications is convenient if the excitation voltage variation ramp is faster, because it helps the motor loading capability.

The transition from inductive to capacitive power factor operation mode is also faster, which is an advantage if the synchronous motor is used as a reactive energy source.

4.2. Current feedback-based compensation with ramp-voltage excitation and $U_s/U_e = ct.$

The ratio between the stator and exciting voltage is kept constant, in the same manner as the constant Volt/Hertz ratio. The variation ramp is computed so, that the exciting voltage reaches the imposed value when the stator voltage is at the rated value, in our case 1 s. The same cases were simulated as in section 4.1.

4.2.1. Results for $\cos\varphi = 1$

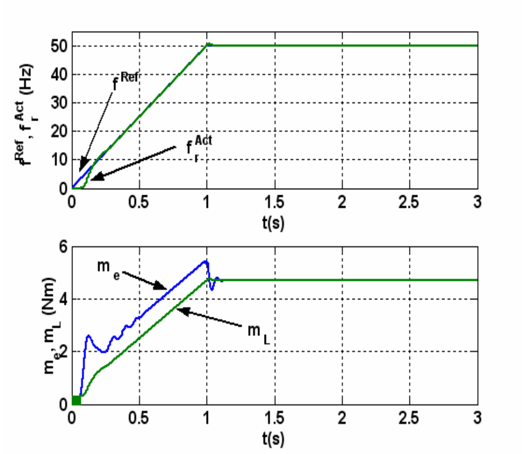

Figure 10. Stator frequency (f_s^{Ref} – reference value, f_s^{act} – actual value) and torque (m_e – electromagnetic and m_L – load) versus time.

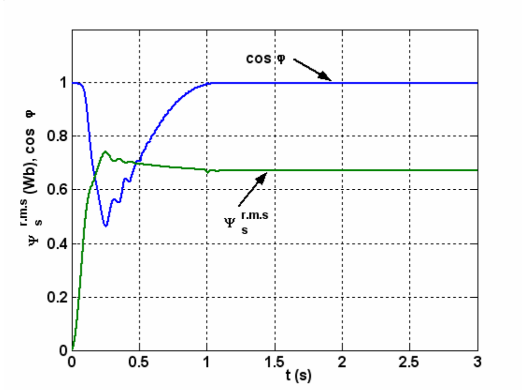

Figure 11. Power factor ($\cos\varphi$) and stator flux r.m.s. value (Ψ_s^{rms}) versus time.

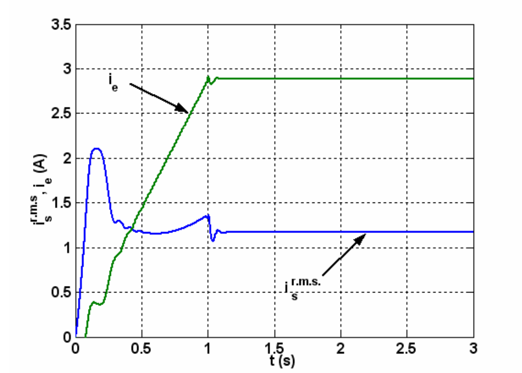

Figure 12. Stator current r.m.s. value (i_s^{rms}) and excitation current (i_e) versus time

In comparison with the previous simulations from section 4.1 it can be observed, that the behavior of the synchronous machine in transient operation mode is improved.

4.2.2. Results for $\cos\varphi = 0.8$

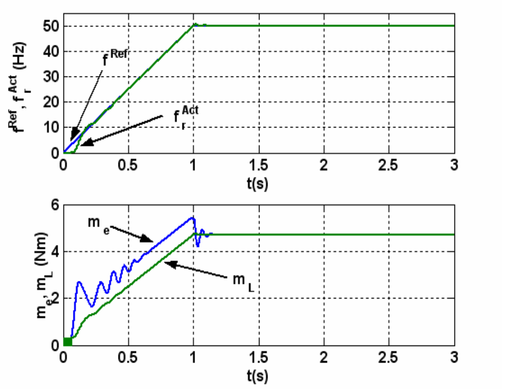

Figure 8. Stator frequency (f_s^{Ref} – reference value, f_s^{act} – actual value) and torque (m_e – electromagnetic and m_L – load) versus time.

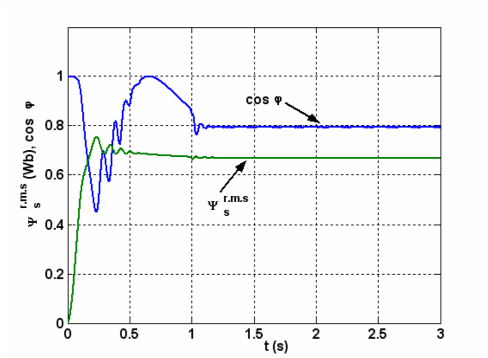

Figure 9. Power factor ($\cos\varphi$) and stator flux r.m.s. value (Ψ_s^{rms}) versus time.

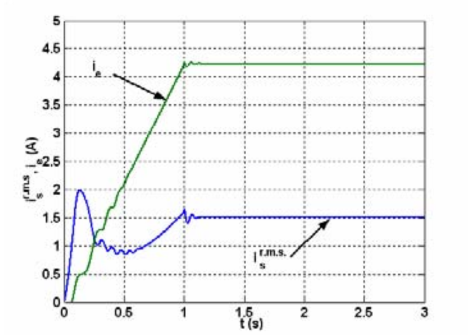

Figure 10. Stator current r.m.s. value (i_s^{rms}) and excitation current (i_e) versus time.

For this particular case, if the constant ratio between the stator- and excitation-voltage is maintained, the simulation results show that it ensures optimal working conditions for the synchronous motor. The torque ripples are considerably reduced, the flux control is better, and the level of the absorbed stator-current is reduced.

5. CONCLUSIONS

With current-feedback based voltage-drop compensation the classical constant Volt/Hertz scalar control method is improved. In case of the synchronous machines, higher drive performances can be obtained if variable exciting current is applied instead of a constant one [7], [8].

In this paper, a ramp-type voltage form was applied for the motor starting procedure. According to the specific applications, the slope of the exciting voltage-ramp can be different from that of the variation ramp of the computed stator-voltage. However, the best results were obtained if the ratio between these two voltages is kept constant during the starting procedure.

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